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Aesthetic impact assessment of solar power plants: An objective and a subjective approach

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ABSTRACT

Solar energy for the production of electric energy is one source of renewable energy which is experiencing most development in recent years. In countries with high solar radiation indices, as is the case of Spain, expectations of installation of large solar power plants are increasing. Most solar power plants are located in rural environments, where the landscape has remained practically unaltered ever since extensive agriculture was introduced. Because of this, one of the most significant environmental impacts of this type of installation is the visual impact derived from the alteration of the landscape. In this work, an indicator is proposed for the quantification of the objective aesthetic impact, based on four criteria: visibility, colour, fractality and concurrence between fixed and mobile panels. The relative importance of each variable and the corresponding value functions are calculated using expert contribution. A study of the subjective aesthetic impact is then carried out using the semantic differential method, to obtain the perception of a sample of individuals of the initial landscapes and of the landscapes altered through the installation of a solar power plant. The indicator and the study of public perception are applied to five real solar power plants, to test their reliability. Subsequently, a different group of individuals is used to determine preferences between the five solar power plants. The study proves that the combined use of objective indicator and subjective study, faithfully explains user preferences corresponding to the combined comparisons of the five cases. It is concluded that the tools proposed for the evaluation of the aesthetic impact of solar power plants are useful for the selection of optimal plant location and most adequate use of panel technology, to minimise aesthetic impact.

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1. Introduction

The world today presents a consumer society with high energy demands facing a scarcity of costly energy resources. Elevated pollution levels and political compromise to comply with the Kyoto protocol has encouraged the use of renewable energies. This has encouraged solar energy production worldwide which has experienced an exponential increase in the last decades. In 2007 alone, global installed capacity increased by 40% and further growth is expected [1].

Rural landscapes present optimal conditions for the location of solar panels which have to be placed along large, open-air expansions of land, highly exposed to sunshine. Amongst other advantages, solar energy is resistant to extreme climate conditions with a life expectancy greater than 35 years and pollution on the environment is reduced to visual impact on the landscape. Following EU regulations, Environmental Impact Assessment (EIA) requires a visual impact analysis for large scale developments such as solar power plant construction projects. It thus becomes necessary to develop methodologies and tools to aid in the evaluation and prevention of visual impact.

One way to quantify visual impact is through the use of indicators [2]. Torres-Sibille et al. [3] present a methodology based on the expert approach [4–6] to develop an objective indicator to quantify the aesthetic impact of wind farms. Similarly to solar energy, wind energy is a type of renewable which requires large expansions of land, and which is often exploited in rural areas. This work makes use of the same methodology to generate a reliable, user-friendly indicator to calculate the magnitude [7] of the aesthetic impact of solar power plants. In addition to this objective calculation, the subjective aesthetic impact is also studied using a public preference approach [5]. Whether a visual impact is approved of or not is determined through cognition; it is the observer viewing the solar plant and processing the information who decides whether the impact is pleasant or unpleasant, whether it is positive or negative. Hence, determining the approval of a visual impact requires an investigation of the viewer population by subjective opinions.

The order of analysis will be as follows: first, indicator variables are identified. Impact functions are calculated for each variable and combined in a weighted sum. The indicator is then applied to calculate the aesthetic impact of five solar plants of different characteristics and a population survey is undertaken to analyse consensus between indicator results and public opinion. Finally, subjective preferences are evaluated using the semantic differential method [8].

Symbols

D_f	fractal dimension (D)
I	impact
OAI	indicator of objective aesthetic impact
S	area (cm^2)
β^*	climatology coefficient

Indices

A	landscape with solar plant A
A_0	landscape without solar plant A
B	landscape with solar plant B
B_0	landscape without solar plant B
ba	background
C	landscape with solar plant C
C_0	landscape without solar plant C
cc	concurrence
cl	colour
D	landscape with solar plant D
D_0	landscape without solar plant D
E	landscape with solar plant E
E_0	landscape without solar plant E
f	fractality
pl	plant
SPP	solar power plant
v	visibility

2. Development of an indicator of objective aesthetic impact of solar power plants

The first step to develop the indicator is to identify the variables of aesthetic impact of solar power plants. From a study of the literature, we suggest that the variables are the visibility of the plant, the colour and, fractality of the panels, and the atmospheric conditions present in the area. The type of panel too can influence the overall appearance of the farm. Each of these variables affects aesthetic impact differently and so construction of an Indicator of Objective Aesthetic Impact of Solar Power Plants (hereafter referred to as OAI_{SPP}) thus requires the development of an individual indicator for each one of these variables: an indicator for the objective aesthetic impact due to visibility (I_v), an indicator for the objective aesthetic impact due to colour (I_{cl}), an indicator for the objective visual impact due to changes in the fractal dimension (I_f) and an indicator for the objective aesthetic impact due to concurrence (I_{cc}).

OAI_{SPP} should enable comparison between impacts generated by different types of plants on different types of landscape. Consequently, for every combination of plant type and landscape type, each I_v, I_{cl}, I_f and I_{cc}, will be a function of the contrast between the plant and the surrounding landscape. Thus, for example, placing a dark panel against a light sky will introduce a contrast in colour, which will generate an impact I_{cc} of value X.

This study uses photographic representations of landscapes. The validity of photographs in landscape assessment is well documented throughout the literature and is now widely accepted [9–11]. The same procedure as that used by Torres-Sibille et al. [3] was applied for the data collection process. Panoramic photographs were taken

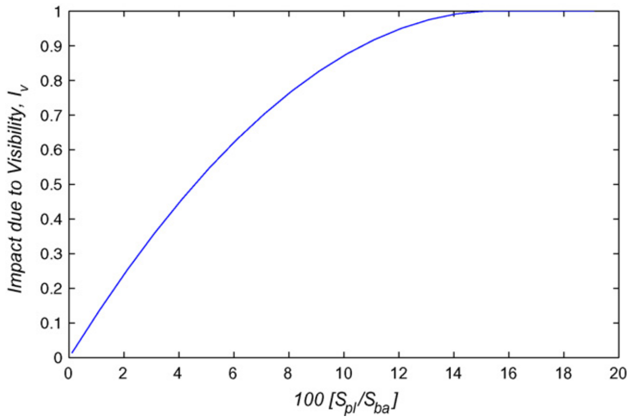


Fig. 1. Value function I_v as given by the experts.

of different solar plants with varying contrasts in visibility, colour, fractality and continuity, and the ratios were calculated.

The calculation procedures for each variable are shown in Section 2.1. Minimum and maximum ratios were assigned impact values of 0 (no impact) and 1 (total impact), respectively. The photographs and their respective results were presented to a panel of ten environmental sustainability experts, who were asked to evaluate the visual impact induced by each variable on a scale of 0 to 1. Subsequently, individual value functions were created for each I_v, I_{cl}, I_f and I_{cc}.

2.1. Impact due to visibility I_v

Visibility refers to the area taken up by the plant with respect to the total landscape area. Introduction of a solar plant into a landscape will decrease the amount of area visible, thereby obstructing the view of the background, hence changes in the visibility ratio will affect visual impact in different ways.

Ratios were calculated for five different photographs by comparing the sum of the areas occupied by the individual panels, i.e. the area occupied by the plant (S_{pl}) to the area taken up by the initial background landscape (S_{ba}). For panels without followers, the area was simply that of the plates, whereas for panels with followers, the area of a panel was the calculated by combining the area of the mast with the area of the plates. The expert evaluation showed that I_v can be described as (Fig. 1):

$$I_v = \begin{cases} 0.004x^2 + 0.128x & \text{for } 0 \le x \le 15 \\ 1 & \text{for } 15 \le x \le 20 \end{cases} \tag{1}$$

where I_v is the aesthetic impact due to the visibility of the solar plant, S_{pl} the area occupied by the panels in view, S_{ba} the area of the photograph, and $x = 100 \times (S_{pl}/S_{ba})$.

When there are no panels in the landscape, the impact perceived by the observer is zero. Visual impact increases with the number of panels and reaches a maximum value of unity when the farm makes up 15% of the view.

2.2. Impact due to colour I_{cl}

Contrasts in hue, saturation and brightness [12] are calculated using the CIELAB colour formulae [13] to generate CIELAB points. For each panel, mean values of the three characterising parameters known as the L, a, b parameters were obtained using Photoshop. Similarly, mean values of the L, a, b parameters were calculated for the area surrounding the farm. As suggested by Bishop [14], in such cases where the object does not display major colour variation, as is the case of a solar panel, the background area to be considered in the analysis should be that of a surrounding ellipse, a little bigger than the object itself.

Light reflection from the panels was omitted from this analysis. A study of the incident rays proves that for the degree of inclination of the solar panels, light reflection will only punctually affect air navigation systems, which overfly the landscape for agricultural purposes, in which case further study is required.

Given the proximity of the solar panels to the ground, and depending on the position of the viewer, impacts in colour may arise so much due to contrasts between the panels and the ground, as between the panels and the sky. Therefore, value functions are developed for both sets of contrasts.

CIELAB points were calculated for three variations of panel colour versus three variations of ground types. Ground types found to be characteristic of solar power plants locations were sand, wheat fields and grass. The procedure was repeated against three variations of sky colour, and assessed with respect to aesthetic impact. The functions resulting from expert evaluation are given by Eq. (2) for contrasts against the sky, and Eq. (3) for contrasts against the ground (Fig. 2).

$$I_{cl_{sky}} = \begin{cases} -\left(\dfrac{190}{10^9}\right)x^2 + \left(\dfrac{978}{10^6}\right)x & \text{for } 0 \le x \le 1400 \\ 1 & \text{for } 1400 \le x \le 1600 \end{cases} \tag{2}$$

$$I_{cl_{ground}} = \begin{cases} \left(\dfrac{4}{10^4}\right) & \text{for } 0 \le x \le 2367 \\ 1 & \text{for } 2367 \le x \le 2500 \end{cases} \tag{3}$$

where I_{cl} is the aesthetic impact due to colour and x is the CIELAB points.

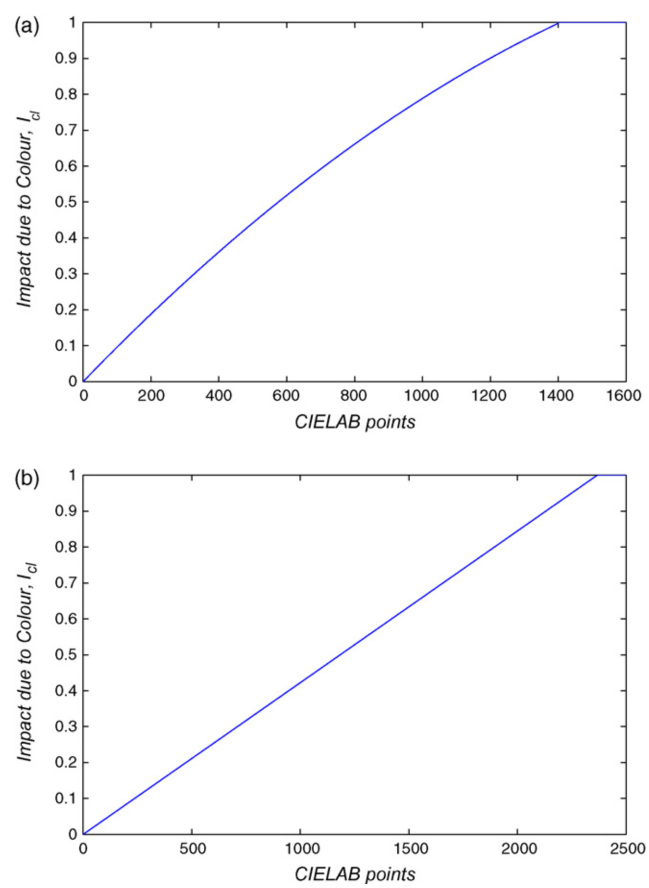


Fig. 2. Value function I_{cl} as given by the experts for colour contrasts against: (a) the sky and (b) the ground.

Table 1
Climatology values

Climatology i	Climatology value X_i
Clear day	1
Other	0.75
Precipitation	0.5
Fog	0.25

Table taken from [3].

At zero CIELAB points, the panels are camouflaged in the background sky or ground and no impact is experienced. The higher the colour differences the greater the impact.

2.3. The climatology coefficient β^*

Visibility and colour will depend on the atmospheric conditions of the area between the object and the observer [12,14], and so the impact due to visibility and colour must be corrected by the atmospheric coefficient.

The value function used to describe the climatology coefficient is taken from Torres-Sibille et al. [3]. Experts were asked to assign values to different types of climatology (Table 1) and β^* is calculated from:

$$\beta^* = \sum_{i=1}^{n} P_i(\beta^* = X_i)X_i \tag{4}$$

where X_i is the value assigned by experts to climatology i and P_i is the probability that climatology i occurs in a given day of the year, i.e. the number of days of climatology i throughout the year divided by the number of days in the year. The climatology data can be obtained from the respective country's Institute of Meteorology.

2.4. Impact due to fractality I_f

Fractality is a measure of artificiality in the geometry of a pattern [15] and it is measured by the fractal dimension D_f. There are no straight lines in nature. Therefore, a solar panel which consists of mere straight lines will generate an impact due to fractality I_f which will contrast against the natural background.

To calculate the fractal dimension, the contour of the solar plant is extracted from the photograph using Photoshop and D_f is generated using the 'matlab' fractal calculation toolbox.

The ratio 'fractal dimension of the farm versus fractal dimension of the main topographic line of the background' was calculated for five photographs and I_f was generated (Fig. 3):

$$I_f = \begin{cases} 100x & \text{for } 0 \le x \le 0.01 \\ -0.085x + 1 & \text{for } 0.01 \le x \le 0.75 \\ -3.745x + 3.745 & \text{for } 0.75 \le x \le 1 \\ -1.048x^2 + 4.145x - 3.097 & \text{for } 1 \le x \le 1.94 \\ 1 & \text{for } 1.94 \le x \le 2 \end{cases} \tag{5}$$

where I_f is the aesthetic impact due to fractality, $x = (D_{f,pl}/D_{f,ba})$, and $D_{f,pl}$ and $D_{f,ba}$ are the fractal dimension of the plant and of the background, respectively.

For a view with no solar panels ($D_{f,pl} = 0$), the impact due to fractality is zero. Assuming that a background is geometrically planar ($D_{f,ba} = 2$), impact will reach a maximum when a straight line is introduced into the scene. This value remains at large levels as more turbines, and thus more lines, are incorporated into the landscape up to the point where adding further turbines will start to convert a group of lines into a plane. At this point

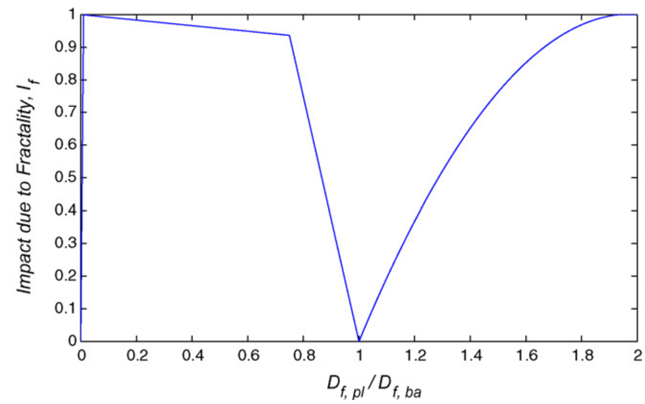


Fig. 3. Value function I_f as given by the experts.

($D_{f,pl}/D_{f,ba} = 0.75$), the impact starts decreasing and becomes zero when $D_{f,pl}$ reaches the value of 2 and the fractal ratio is unity. The remainder of the value function shows impact increasing as more planes are created on top of a planar background. As three-dimensionality is approached, the impact generated by the contrast against a planar background is again at its highest.

2.5. Impact due to concurrence I_{cc}

Concurrence refers to the similarity in concentration of two types of solar panels within one solar plant. Each panel type can have a different concentration. For example, in Fig. 4 the concentration of the panels without followers is more intensive than the concentration of the panels with followers. The contrast between both concentrations due to concurrence of typologies will cause an impact.

Concurrence in a solar plant is measured as follows:

$$\text{concurrence} = \frac{\alpha a + \beta b}{a + b} \tag{6}$$

where a is the area occupied by panels with followers, b the area occupied by panels without followers, α the density of type a panels and β is the density of type b panels.

Similarly to visibility, colour and fractality, a value function for concurrence was obtained from expert assessment (Fig. 5):

$$I_{cc} = Ae^{(-(x-\mu)^2/2\sigma^2)} \tag{7}$$

where $A = 0.99$, $\mu = 0.5125$ and $\sigma = 0.1416$.

Fig. 5 shows that according to the experts, from the values given by the experts and adjusting curves, the impact due to concurrence can be described by a Gaussian normal. The greatest impact occurs when the proportions of both types of panel distributions are similar (concurrence = 0.5) and impact is zero, for low and high levels of concurrence. Given that the function is asymptotic along the x-axis, in a strict sense the values cannot cancel out at both extremes, although in practice they can be considered null (error smaller than 1%). To simplify the calculations, adjusting the curve

Fig. 4. Concurrence explained. Picture taken from Solaer [32].

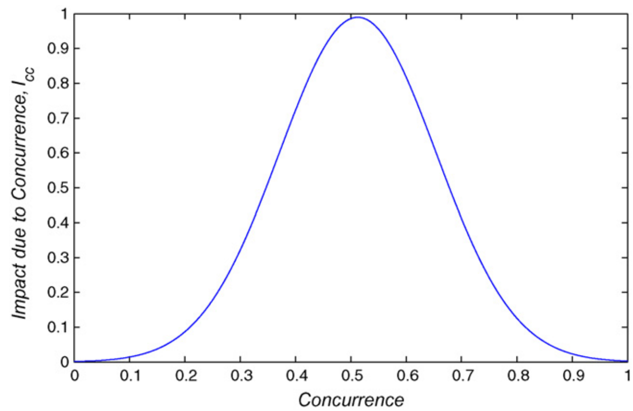


Fig. 5. Value function I_{cc} as given by the experts.

to a Gaussian normal was considered valid, and this was confirmed with the experts.

2.6. Operational definition of OAI_{WF}

I_v, I_{cl}, I_f and I_{cc} are combined in a final formula to give the Objective Aesthetic Impact of a Solar Power Plant installed on a landscape. This formula takes the form of a weighted sum, in which the weights have been given by expert judgement in a Delphi procedure [16,17] and analysed by means of the analytical hierarchy process (AHP) in a multicriteria approach. The program Expert Choice 2000 was used to carry out the calculation of the weights. Greatest importance was attributed to visibility, which was considered more than three times as important as the second most important attribute, colour. Fractality and concurrence were assigned smaller weights, but were still significant.

$$\mathrm{OAI}_{SPP} = \beta^*(0.64 I_v + 0.19 I_{cl}) + 0.09 I_f + 0.08 I_{cc} \quad (8)$$

3. Application of OAI_{SPP} to five solar power plants

OAI_{SPP} was applied to study the objective aesthetic impact at close-up view of five different solar power plants located throughout Spain, solar plants A–E.

Solar plants A and B can be found in the eastern Spanish region of Teruel. The first farm consists of 20 installations of panels without followers generating a total of 1.92 MW and is situated in a mountainous natural area. Solar plant B is also comprised of panels without followers but is much smaller and generates 0.2 MW. As opposed to the other four plants, B is surrounded by numerous trees.

Solar plant C is sited on a rocky, anthropologically altered landscape in the vicinity of the town of Castellón (eastern Spanish coast). It consists of seven installations of panels without followers rated at 0.7 MW, spread out over an area of 1.75 ha.

Finally, solar power plants D and E, rated at 3 and 1 MW, respectively, are situated in the flat-land prairies of Cuenca (Spanish inland).

3.1. Analysis for I_v, I_{cl}, I_f, I_{ct} and β^*

The analysis was carried out for close-up views of the solar plants as a worst case scenario. Photographs of the plants are made from those points which offer maximum visibility of the installations at each plane, and at each cardinal point wherever possible [3].

Table 2
β^*, I_v, I_{cl}, I_f, I_{cc}, and OAI_{SPP} calculated for the five solar power plants

Solar power plant	β^*	I_v	I_{cl}	I_f	I_{cc}	OAI_{SPP}
A (Teruel)	0.69	0.64	0.39	0.55	0.00	0.39
B (Teruel)	0.69	0.07	0.19	0.59	0.00	0.10
C (Castellón)	0.75	0.29	0.19	0.76	0.00	0.22
D (Cuenca)	0.67	0.54	0.57	0.75	0.32	0.39
E (Cuenca)	0.67	0.56	0.53	0.43	0.09	0.36

For each photograph, visibility ratios, colour ratios, fractality ratios and concurrence values were computed and translated into impact values using the value functions above. Subsequently, the average impact value of each variable was calculated. The climatology coefficient was calculated for each plant using atmospheric data obtained from the Spanish Meteorological Office website. The resulting values are presented in Table 2.

Inserting the values for I_v, I_{cl}, I_f and I_{ct} into OAI_{SPP} as given by Eq. (8), the objective aesthetic impacts of the six solar power plants are, in order from most impacting to least impacting, 0.39 for solar plants A and D, 0.36 for solar plant E, 0.22 for solar plant C, and 0.10 for solar plant B (also shown in Table 2).

3.2. Discussion of results

Solar power plants A and D are the most impacting plants with an impact value of 0.39. Plant A owes much of its position to its high degree of visibility ($I_{v_A} = 0.64$). Furthermore, moderate colour contrasts and large fractality contrasts between the linear panels and the green, natural background ($I_{cl_A} = 0.39$; $I_{f_A} = 0.55$) also help increment the impact of the plant. On the other hand, the impact due to concurrence is null, as the panels are all of the same type and without followers.

Solar plant D is equally impacting. This plant consists of follower panels which have lower spatial density and will thus generate an impact due to concurrence ($I_{cc_D} = 0.32$). Strong colour and fractal contrasts between the panels and the skyline ($I_{cl_D} = 0.57$; $I_{f_D} = 0.53$) combined with a high degree of visibility ($I_{v_D} = 0.54$) contribute to place this plant in top position.

Equally visible is solar plant E ($I_{v_E} = 0.56$). This plant scores just below A and D ($\mathrm{OAI}_{SPP_E} = 0.36$). This is largely due to lower fractality contrasts and a negligible concurrence impact ($I_{f_E} = 0.43$; $I_{cc_E} = 0.09$). Whereas plant D is made up of follower panels which generate strong fractal contrasts against a linear horizon, solar plant E is comprised primarily of sleek panels without followers. Furthermore, plant D spreads out over an area twice as big as that occupied by the panels themselves, whereas plant E's panels agglomerate on a ground area of equal size.

Null concurrence contrasts can be appreciated in the Castellón solar plant together with low colour contrasts and reduced visibility ($I_{cl_C} = 0.19$; $I_{v_C} = 0.29$). Nevertheless, the contrast between the fractal panels and the natural background increase the plants total impact ($I_{f_C} = 0.76$; $\mathrm{OAI}_{SPP_C} = 0.22$). Furthermore, out of the three regions, Castellón is the only one for which the atmospheric conditions make a difference in the overall impact, for it exhibits the highest climatology coefficient of all ($\beta^*_C = 0.75$). This is due to the geographical location of the region which enjoys much of the sunshine characteristic of the coastal Mediterranean climate.

Least impacting of all is solar plant B with a total impact of 0.10. The plants position on the impact scale results from a combination of very low visibility ($I_{v_B} = 0.07$), low colour contrasts ($I_{cl_B} = 0.19$) and negligible impact due to concurrence. Even though strong fractal impacts can be appreciated given the abundant vegetation in the area.

Finally, it is interesting to note that both plants C and D show similar fractal impacts. However, for C, the fractal dimension of the plant is smaller than that of the background and for D the fractal dimension of the plant is bigger than that of the background.

4. Validation of the indicator

For the validation of the indicator this investigation will follow the validation procedure introduced by Torres-Sibille et al. [3]. Three types of validation are considered: Sui validatio or design validation, Scientatis validatio or output validation and Societatis validatio or end-use validation [18,19]. Sections 2 and 3 have dealt with the first two validations. This section will look at the social validation.

4.1. Consensus between indicator results and public opinion

The aim of the social validation is to ensure that the indicator results reflect public preferences. OAI_{SPP} has ordered the solar plants according to their aesthetic impact ($A = D > E > C > B$). If the indicator is to reflect public preferences, this order should correspond to the order chosen by the public. Five photographs, each a representative close-up view of a solar power plant (Fig. 6), were chosen and passed in a survey to a total of 123 people. The photographs of solar plants A–C were taken on clear days, whereas those of solar plants D and E were taken on typical days of precipitation.

The subjects, who were students and teachers of the engineering and social-sciences disciplines, were shown pairs of photographs and were asked to order them according to how impacting they considered each solar plant to be. Seventy people compared solar plants B, C and E with each other. Thus, each person evaluated three paired combinations (B and C, B–E and C–E). The remaining seven combinations (A and B, A–C, A–D, A–E, B–D, C and D, D and E) were compared by different groups of 40 subjects. In total, 490 evaluations were analysed. For all the evaluations, the subjects were asked to record why they made the choice that they made. No further information or material, other than the photographs themselves, was given to them so as not to bias their judgement.

The results of the survey are shown in Table 3. The left-hand side of the table shows the 15 possible pair-wise combinations, as well as the sequences that may be chosen within each combination. For example, for the combination A and B, the possible sequences are A preferred over B ($A > B$) and B preferred over A ($B > A$). The number of people choosing each specific sequence is also given, and the preferred sequences are written in bold. Additionally, the sequences which match the order given by the indicator have been underlined.

The table shows that for the subjects, the order of impact is $D > A > E > C > B$. Except for the combination A–D the resulting sequence for both indicator and sample population it is the same.

4.2. Subjects' decisions according to preferences

To verify the validity of the subjects' decisions, it was necessary to ensure that the subjects indeed chose each sequence according to some preference and not in a random manner. Thus, we need to confirm that the probability the subjects decided on a sequence according to some preference is statistically significant. This probability is given by Eq. (9):

$$P(H_1|N,s) = \frac{P(s|N,H_1)(1-p_0)}{P(s|N,H_1)(1-p_0) + P(s|N,H_0)\,p_0} \tag{9}$$

where:

$$P(s|N,H_1) = \frac{N_1!N_2!}{(N_1+N_2+1)} \tag{10}$$

$$P(s|N,H_0) = (p_0^{N_1})(1-p_0)^{N_2} \tag{11}$$

where $P(H_1|N,s)$ is the probability that the subjects decided according to some preference, $P(s|N,H_1)$ the probability that sequence s was chosen according to given preferences, $P(s|N,H_0)$ the probability that sequence s was chosen at random, H_1 the hypothesis that sequence s is chosen due to preferences, H_0 the null hypothesis that sequence s was chosen at random, p_0 the probability of the null hypothesis, s the preferred sequence within a pair, e.g. sequence A over B, N the number of subjects evaluating a combination, and N_i is the number of people choosing sequence i.

The sample size of five photographs was used to reduce the probability that the subjects choose a sequence at random. A sample size of five gives ten possible combinations. Under the null hypothesis and assuming that the probability of choosing any one sequence is equal to 0.5, the probability that the subjects choose a sequence of photographs at random is reduced to 0.1%.

Table 3 shows that the subjects had a preference for a specific sequence in 6 of the 10 sequences. In these cases, the probabilities are greater than 90%, five of which surpass the 95% boundary. These values are statistically significant. Only four cases exist for which the subjects' answers are not as highly consistent. These are $A > E$ and $E > C$ with probabilities of 19% and 30%, respectively, and $D > A$ and $D > E$ with probabilities greater than 70%.

The indicator results show that even though solar plants A, D and E exhibit different characteristics, they generate objective impacts of similar magnitude ($OAI_{SPP_A} = 0.39$; $OAI_{SPP_D} = 0.39$; $OAI_{SPP_E} = 0.36$), and so it is not surprising to see that the subjects did not choose between combinations A–E, A–D and D and E with significant consensus.

Combinations A–D and D and E show a lower probability than for most other cases, but nevertheless, the odds that subjects choose according to preference as opposed to at random are 5–1 and 3–1, respectively. On the other hand, combinations A–E and C–E exhibit very low probabilities and so it is interesting to study the reasons the subjects gave for selecting one sequence over another.

Whereas plant E is larger and generates a stronger impact, photograph C shows clear weather conditions which contribute to accentuate its impact. Furthermore, the colour contrast between the plant and the ground is much stronger than the colour contrast shown in photograph E where the light-reflecting farm is largely camouflaged against a light grey sky.

The survey population also experiences difficulties in choosing a preferred sequence from combination A–E. The subjects considered A more impacting than E primarily due to the weather conditions displayed in photograph A which make the plant more visible and colour-striking, and hence more impacting, whereas the cloudy weather conditions in E strongly mitigate colour contrasts between the panels and the background sky. The subjects also mentioned that as solar plant A is placed within a walking route, surrounded by abundant and "lively" vegetation, it is more hindering to the natural environment than plant E which seems to be situated on a "remotely harvested" crop field. However, others stated that precisely because there are no objects surrounding plant E, this plant draws more attention to the eye, breaking the horizon line, and it is hence more impacting. It is interesting to note that regardless of which plant was considered more impacting, the majority of the answers coincide in that photograph A presents a more "enjoyable" environment.

Similar arguments hold for choosing sequence $A > D$, only that in this case, according to the subjects, the larger number of follower-panels combined with the strong colour contrasts they

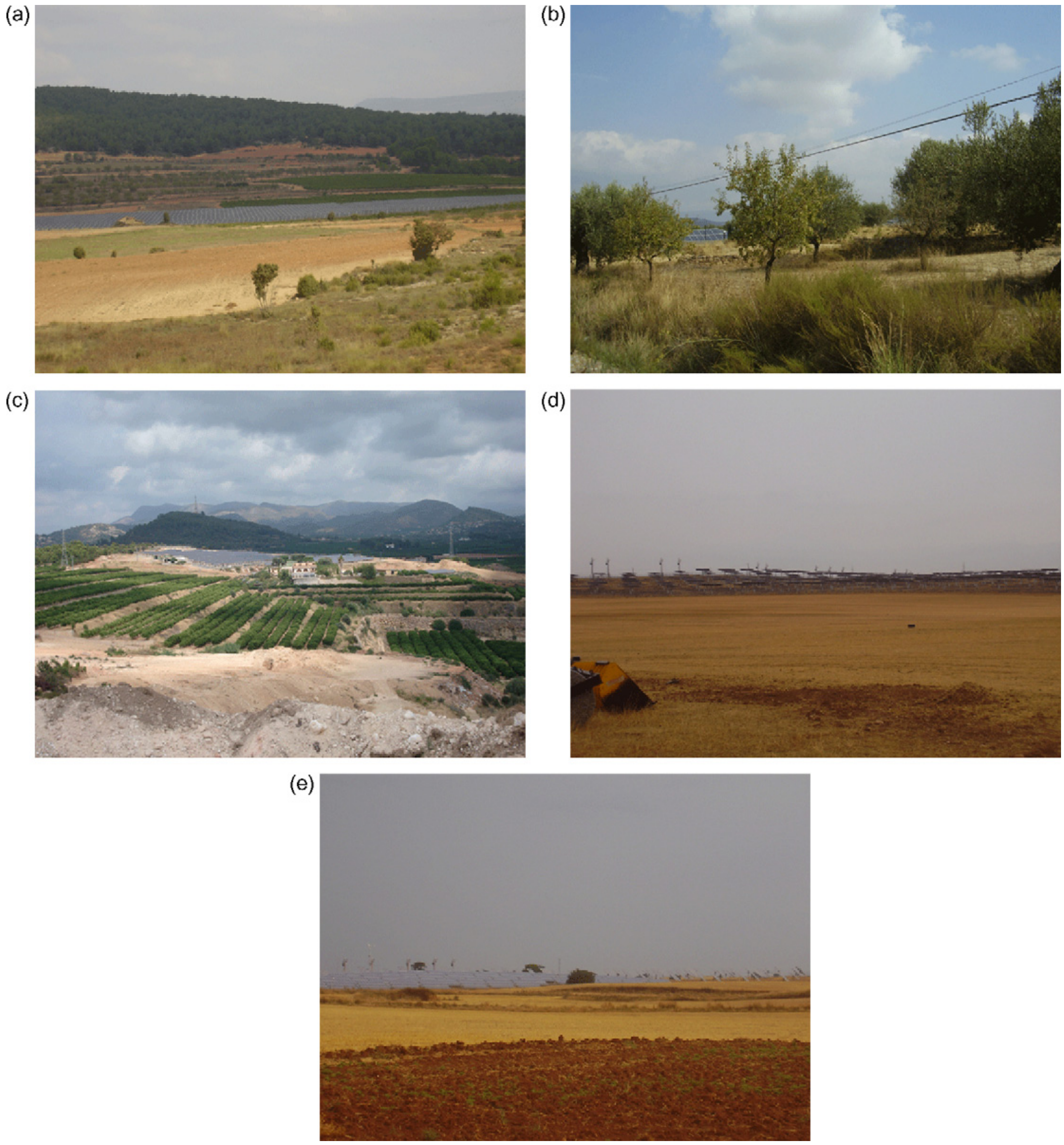


Fig. 6. Photographs of (a) solar power plant A, (b) solar power plant B, (c) solar power plant C, (d) solar power plant D and (e) solar power plant E. These photographs were used for the social validation and for the semantic analysis.

generate against the light sky, increase the probability that a subject should choose plant D as more impacting than A. Colour contrast too is the primary reason why D is chosen over E, even though E is considered more impacting by some because it is larger in size. Additionally, a general remark is that photograph D displays a "gloomy" atmosphere as opposed to the "lively" environment presented in A.

At this point, it is important to note that whereas the subjects can distinguish between the most impacting plants of combination A–D with a fairly high probability (83%), the indicator grants both plants equal impact ($\mathrm{OAI}_{\mathrm{SPP}_A} = \mathrm{OAI}_{\mathrm{SPP}_D} = 0.39$). In making their decisions, the subjects are taking into account so much objective variables, as subjective feelings. They are considering size and colour contrasts in addition to enjoyability, liveliness and

Table 3
Table showing the possible sequences (s_i) within a combination, the number of people choosing a particular sequence (N_i) and the probabilities related to each sequence

Combination	s_1	s_2	N_1	N_2	$P(s\|N, H_1)$	$P(s\|N, H_0)$	$\frac{P(s\|N,H_1)}{P(s\|N,H_0)}$	$P(H_1\|N, s)$
AB	**A > B**	B > A	31	9	8.92×10^{-11}	9.09×10^{-13}	98.07	0.9899
AC	**A > C**	C > A	33	7	1.31×10^{-9}	9.09×10^{-13}	1.44×10^{3}	0.9993
AD	A > D	**D > A**	12	28	4.37×10^{-12}	9.09×10^{-13}	4.80	0.8276
AE	**A > E**	E > A	22	18	2.51×10^{-13}	9.09×10^{-13}	0.24	0.1913
BC	B > C	**C > B**	8	32	3.17×10^{-10}	9.09×10^{-13}	348.71	0.9971
BD	B > D	**D > B**	10	60	3.55×10^{-14}	8.47×10^{-22}	4.19×10^{7}	1.0000
BE	B > E	**E > B**	17	53	1.79×10^{-18}	8.47×10^{-22}	2.11×10^{3}	0.9995
CD	D > C	**D > C**	11	29	1.06×10^{-11}	9.09×10^{-13}	11.60	0.9206
CE	E > C	**E > C**	16	24	3.88×10^{-13}	9.09×10^{-13}	0.43	0.2991
DE	**D > E**	E > D	45	25	2.18×10^{-21}	8.47×10^{-22}	2.5757	0.7203

gloominess. Hence, an analysis of aesthetic impact would incorporate a study on objective aesthetic impact and conveniently complement it with an investigation on subjective aesthetic impact. Consideration of both analyses would result in the most adequate representation of how the public perceives the alteration.

Analysing subjective reactions requires a cognitive study of people's preferences for solar power plants. There is yet no psychological research specific to solar power plants in the literature. In the following section, a subjective study is presented where cognitive aspects of solar plants are analysed. The aim is to unite both objective and subjective aesthetic impact of solar plants.

5. Semantic analysis of subjective aesthetic impact of solar power plants

The previous section presented an analysis carried out by experts to evaluate the objective aesthetic impact of solar power plants. A social survey was also carried out to establish consensus between the indicator results and public preference. Although for most combinations consistency was achieved with statistically significant probability values, further study on subjective judgement was recommended. Integrating expert knowledge with public evaluative reaction constitutes an important step towards the holistic approach of landscape assessment, which is gaining more strength in landscape evaluation practice [5].

The objective of this study is to analyse the behaviour of human perception towards the aesthetic impact of different solar power plants. For this, we will apply the sematic differential method [8,20]. Differential semantics is a technique used to analyse the affective meaning of things and proves particularly suitable to a type of problem in which the aim is to measure the overall impression of an environment [20]. Studies have applied this technique to evaluate architectural interiors and product design, and results have always demonstrated high reliability and validity [21–23]. Differential semantics has also been applied in landscape analysis, although in very limited amounts [24]. Given the positive findings of their study, Karlsson et al. [22] suggested its wider use in landscape analysis.

The objective of solar power plants is the generation of "clean" energy. The expert analysis, however, proves that solar plants induce a visual impact of given magnitude which will affect the emotional state of the viewer. The stimulation of appropriate emotions has been found to enhance the value of physical products [25,26]. Semantic differential analysis thus becomes appropriate in the design and maintenance phases of solar plants which seek to mitigate visual impact and generate "clean" energy.

The semantic profiles of the landscapes, both pre- and post-installation of the solar plant are compared and evaluated. Photographs of the landscapes with the solar plants A–E (Fig. 6), and photographs of the initial landscapes A_0–E_0(Fig. 7) were shown to a group of individuals of homogeneous characteristics. Studies based on differential semantics have shown how different population groups can express different perceptions of the same product [27,28]. The subjects were chosen to be university students from the engineering disciplines, between the ages 20 and 25 years. They were also selected on the premises that they were not familiarised with the landscape or the type of landscape under analysis.

Every photograph was evaluated by 35 individuals on 10 Likert scales each representing a different semantic concept. The subjects answered as they agreed or not with the statement. Unipolar scales were used to avoid possible ambiguities arising from bi-polar antonyms, and these were made to vary between -3 and $+3$ to ensure greater precision and internal validity of the method while at the same time allowing for simplicity.

The concepts used in this investigation were selected based on studies by Küller [29], and adapted to suit the Spanish language. These concepts are: "Pleasantness", "Complexity", "Coherence", "Openness", "Affection" and "Originality". Küller [21,29] used these scales to analyse architectural landscapes [21,29] and Karlsson et al. [22] later applied the same semantic environment to product design [22]. Additionally, it was found necessary to include scales of "Naturalness" and "Liveliness" as landscape descriptives used by Real et al. [30], "Stimulation" as a descriptive measure of the emotional state [31] and finally "Degree of Protection" as a direct measure of the value of the landscape.

Table 4 shows the 10 concepts defined. Following Küller's [20] general administration recommendations, if participants asked about the meaning of a concept they were encouraged to 'think of the meaning he/she put into the word in this context'. If they were not satisfied, the test-leader could provide one or more of the other words in the same factor as an association [22].

5.1. Significant differences between the solar plants

The graphs below (Fig. 8(a) and (b)) show the semantic results of the pre- and post-intervention photographs. In general, whereas for photographs A_0, A and B_0, B the results are positive for most axes, for D, D_0, E and E_0, the results are negative. Landscapes A_0, A and B_0, B are perceived as natural and lively, pleasant and stimulating, deserving a fair amount of protection. This is not the case for D_0, D or E_0, E, which impact because they are neither natural nor lively, because they are relatively unpleasant and of little stimulation. According to the survey, landscapes D_0, D and E_0, E deserve less protection than landscapes A_0, A, with landscape D_0, D scoring lower than all other landscapes in every axis. Landscape C_0, C on the other hand is one which causes indifferent reactions in these axes.

Solar plants A and B are both equally pleasant, natural and lively and deserve an equally high degree of protection (protection $= 2.4$). The subjects, however, consider A more impacting than B with a very high probability of 99%. When the subjects were asked why they thought plant A was more impacting than plant B, they all commented on the difference in size and noted that plant B is hidden behind trees as opposed to plant A which is at full exposure. Additionally, the semantic analysis tells us that plant A is perceived as more stimulating and open than B. Further research would consist in establishing a relationship between 'Stimulation' and the amount/type of vegetation and colour in the photograph, as well as plant area. This analysis in which subjective feelings are correlated with objective variables can be done via the holistic approach.

Plants A and E generate different semantic impacts. The analysis shows that plant A is considered more pleasant, natural, stimulating and lively, and deserves more protection than E. However, even though there are semantic differences, there is no significant consensus among the subjects. In fact, the probability that the subjects decide which of the two farms is more impacting according to preferences is a very low 19%. This is because when the subjects choose between either of the plants they take into account both, objective variables and subjective feelings. Although both plants generate subjective impacts, it is the objective variables which decide upon the magnitude of the impact. Here, the subjects noted that although plant E seems to be larger in size, the strong colour contrasts in A and the clear weather conditions displayed in the photograph minimise impact differences between both farms. Similarly to combination A and B, a correlation analysis would determine the relationship between the objective variables and the impact of the farm.

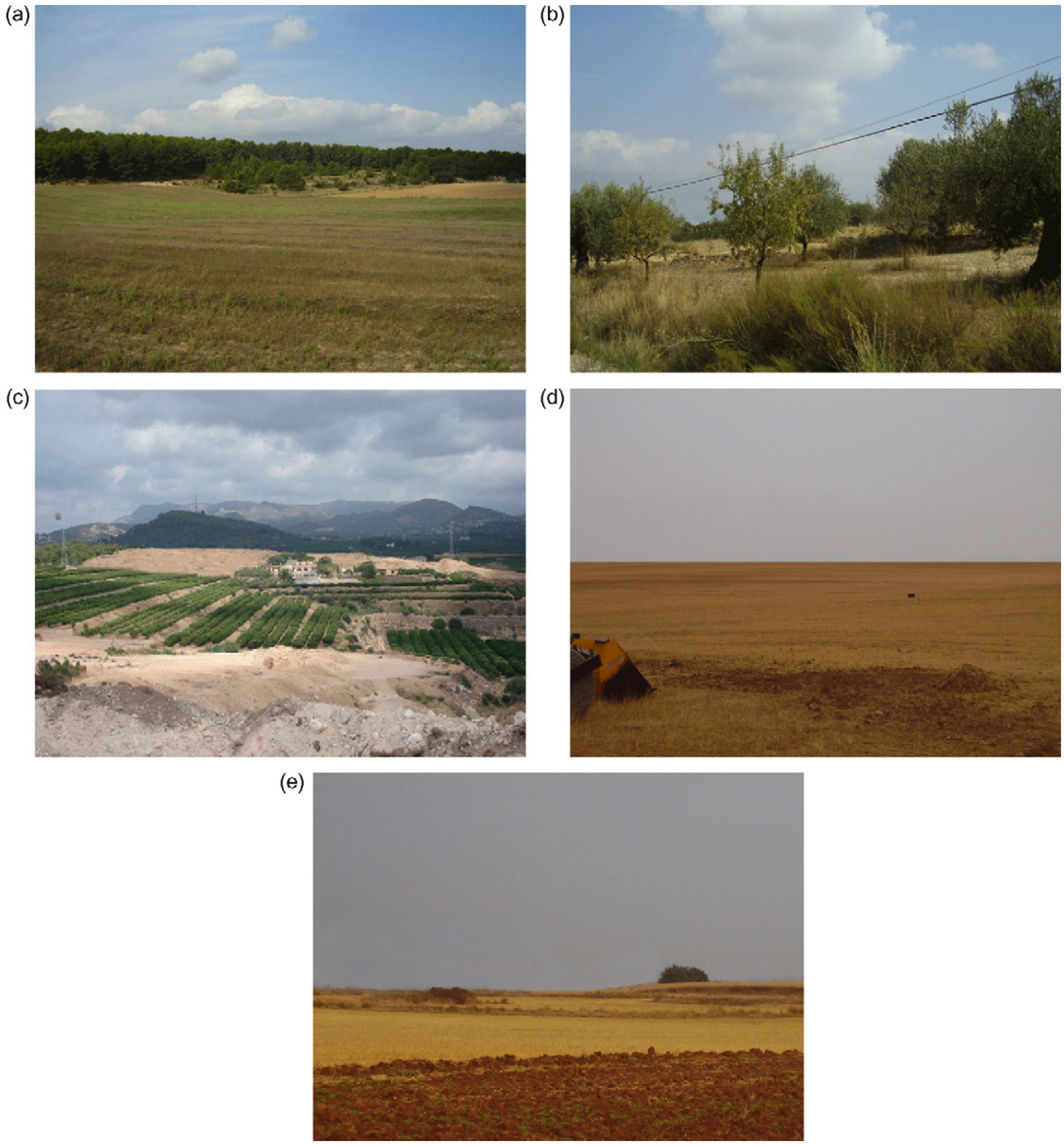


Fig. 7. Photographs of (a) initial landscape A_0, (b) initial landscape B_0, (c) initial landscape C_0, (d) initial landscape D_0 and (e) initial landscape E_0. These photographs were used for the semantic analysis.

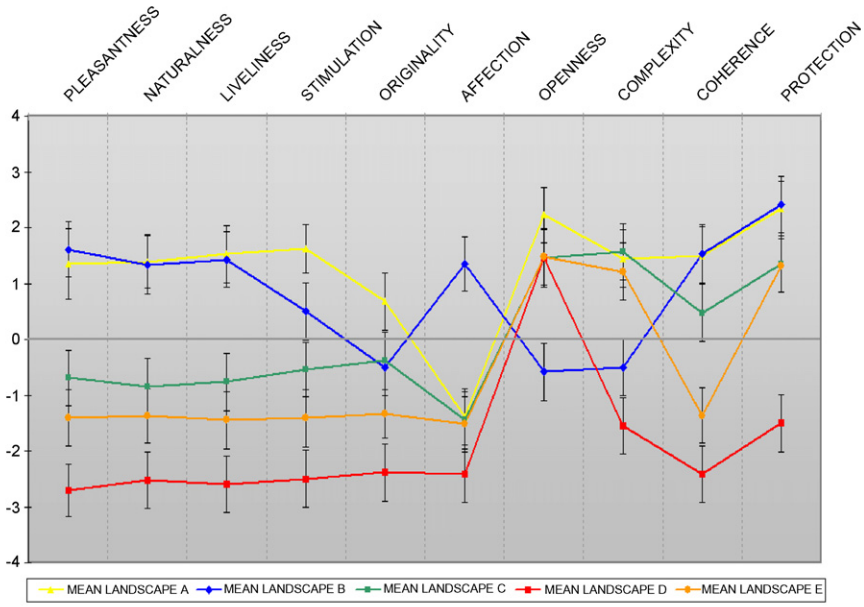
A semantic comparison of landscapes B and C conveys significant differences in all axes. Whereas landscape B scores along the positive region, C seems to produce indifferent reactions among observers. Accordingly, the subjects fully agree that C is more impacting than B as the former constitutes a larger area.

Between C and D there are significant differences in pleasantness, naturalness, stimulation, liveliness and protection, with C always scoring above D. Accordingly, the subjects also decide with a significantly high probability that D is more impacting than C.

Table 4
The semantic concepts and their description

Concept	Description
Pleasantness	The degree of pleasantness, beauty and security which the individual experiences in the environment
Complexity	The environment's diversity
Coherence	How well the various components in the environment seem to fit and function together
Openness	The openness and degree of demarcation of the space
Affection	An age as well as a feeling of the old and genuine
Originality	The unusual and surprising in the environment
Naturalness	The environment's authenticity, often connoted to elements of flora and fauna
Liveliness	The degree of life-emanation of the environment
Stimulation	The degree of stimulation, suggestion and interest which the individual experiences in the environment
Degree of protection	The degree of protection attributed to the environment

Table adapted from Karlsson et al. [22] and Küller [21].



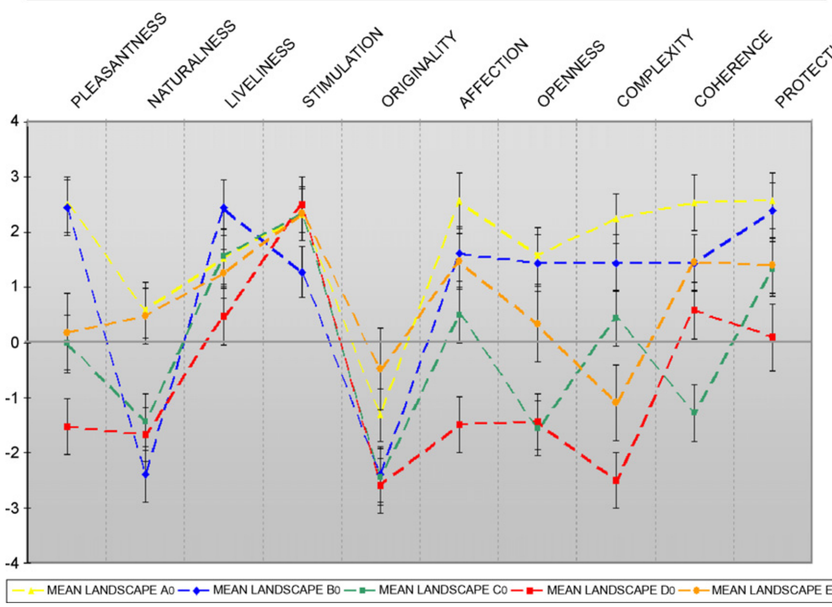


Fig. 8. Semantic profiles of (a) the solar power plants and (b) the initial landscapes.

No significant differences in the cognitive aspect can be appreciated between C and E, nor can the subjects decide with a significantly high probability which of the two plants is more impacting (probability = 30%). This is not the case for combination E and D, which presents significant differences in all axes and a degree of consensus of over 70%.

Finally, a general point is that there are few significant differences between the farms for the concept "openness". This is because all landscapes presented are of large expanses of land, which have not been blocked or surrounded by objects such as mountains and trees. Differences only exist in combinations which involve landscape B as this is the only landscape that presents an environment surrounded or "closed in" by vegetation.

5.2. Significant differences between initial and altered landscapes

This section will determine significant differences between the initial landscape and its respective altered landscape. The graphs concerned are shown in Fig. 9(a)–(e).

When a solar plant is installed all landscapes lose out on affection. This is understandable as affection alludes to tradition, to the past and the old, and solar plants are a relatively new type of installation. A solar plant will also increase the complexity of a landscape, and with the exception of landscape B, its artificial aspect will reduce the landscape's naturalness. Solar plant B is very small in size and does not seem to affect the naturalness of the background. It does, however, manage to enclose the landscape and make it more affectionate, complex and original. It is interesting to see that scarce visibility of a plant can generate significant differences in these concepts. Interesting too is that contrary to what occurs in landscape B, installing a plant in landscape E reduces the level of originality significantly. No other plant affects the originality of a landscape.

Another landscape which becomes enclosed by the introduction of a solar plant is D, for which the panels obstruct the entire horizon line. Similar to landscape D the panels in landscape E are also placed along the entire horizon line, however, in this case, the light reflects such that the colour contrasts between the

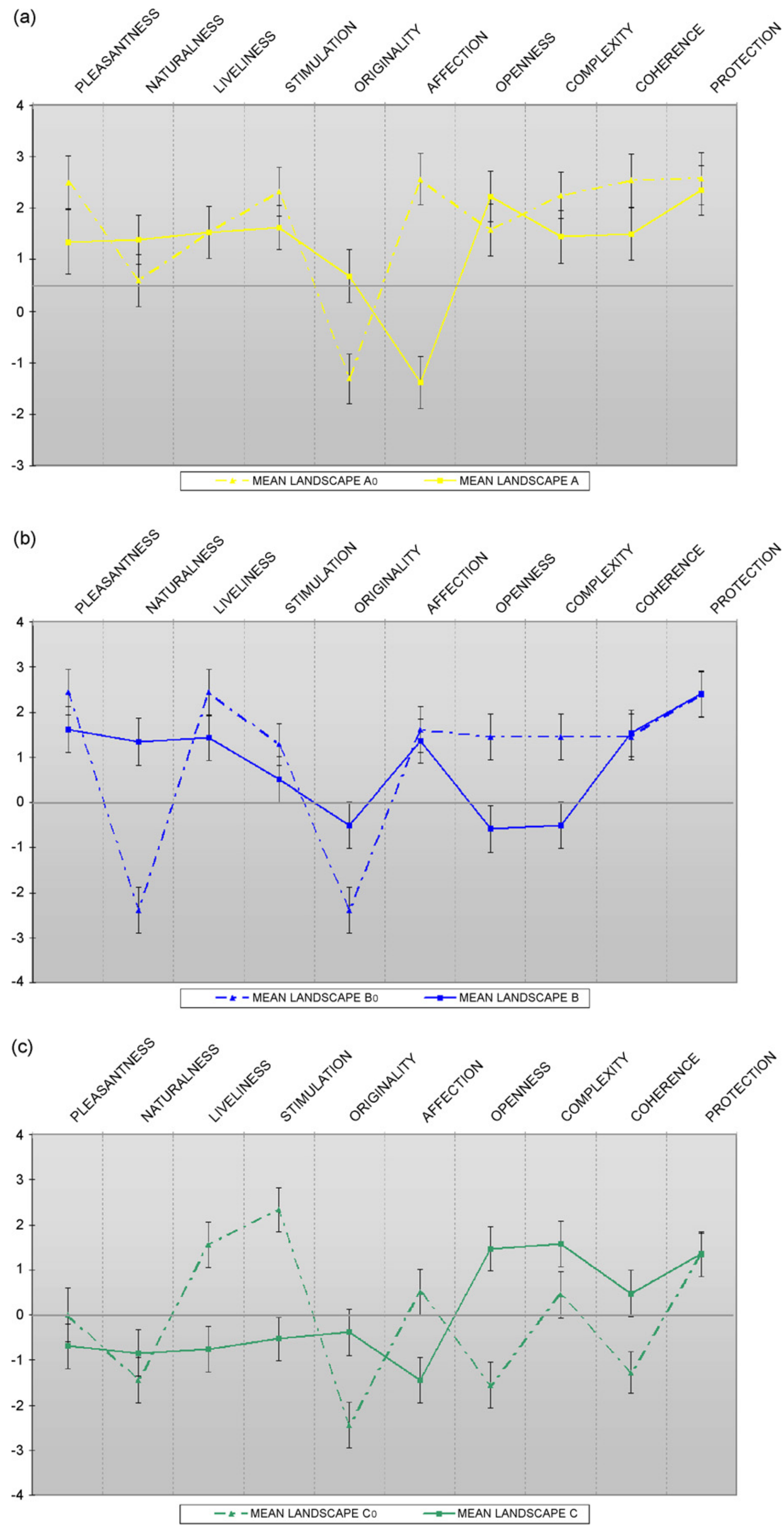


Fig. 9. Semantic profiles of (a) landscape A versus landscape A_0, (b) landscape B versus landscape B_0, (c) landscape C versus landscape C_0, (d) landscape D versus landscape D_0 and (e) landscape E versus landscape E_0.

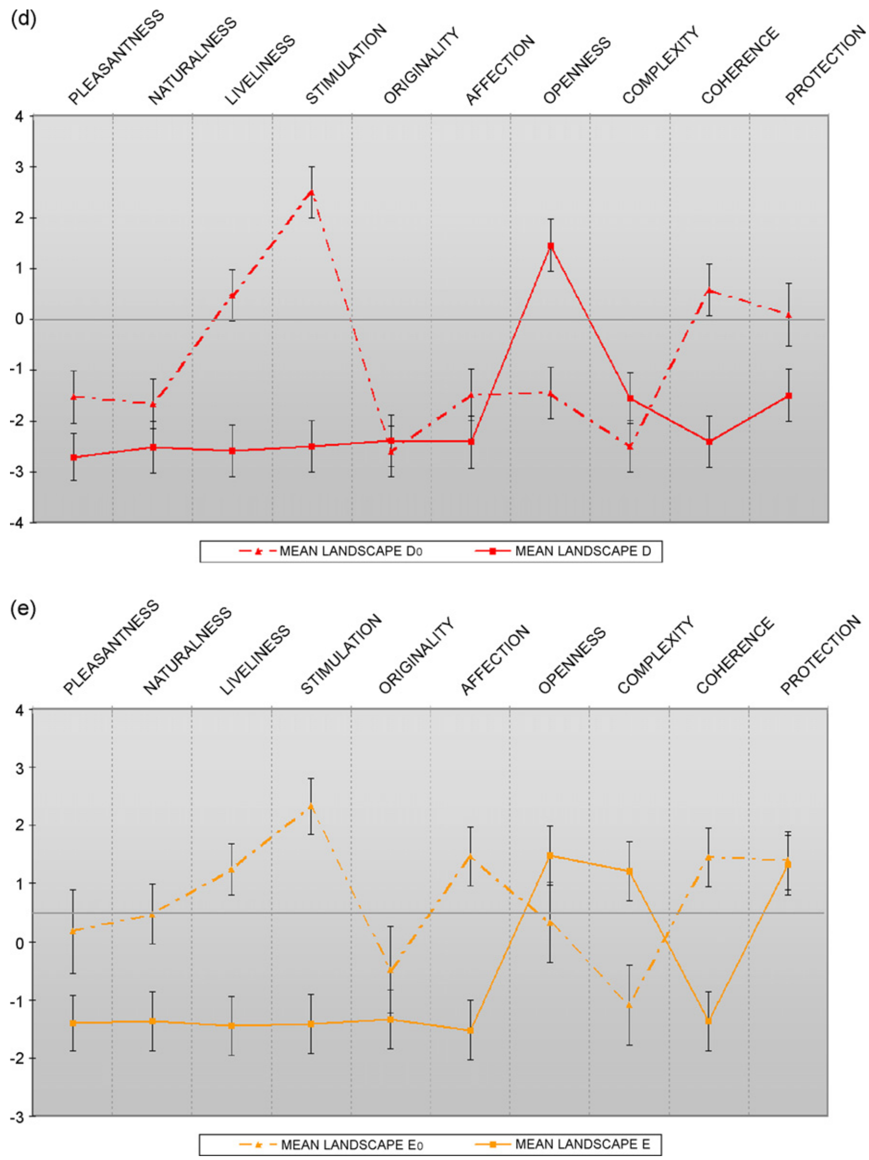


Fig. 9. (*Continued*).

panels and the sky are not as strong making the panels less visible.

Landscapes E_0 and D_0 are the only landscapes affected stimulation-wise by the installation of a solar plant, which makes them less stimulating. In comparison to the remaining photographs, E and D present two landscapes of similar characteristics; both showing plants placed along the horizon line of two harvested corn fields.

With the exception of B for which the solar plant does not affect coherency, and excluding C, all initial landscapes are more coherent. C_0 displays an agrarian landscape with initial elements of industrialisation. In this case, a solar farm would “fit in” with the already anthropologically altered landscape. And it is precisely this gain in artificiality which makes the landscape less life-emanating when the solar plant is incorporated. It is interesting to note that this is the only landscape for which life-emanation changes significantly with the incorporation of a solar plant.

In general, further research should seek to determine relationships between the plant characteristics and the different reactions. For example, how fractality may relate to affection and naturalness, how size may affect complexity and originality, how colour contrasts may close-in landscapes, or which farm characteristics influence significant differences in stimulation and life-emanation.

According to the indicator, the most impacting solar plants are A, D and E. These plants reduce the landscapes’ pleasantness significantly whereas for B and C no changes in this concept can be observed. A point worth researching further is that significant differences should arise in this particular axis for the most impacting plants only. In particular, it would be interesting to analyse whether all the concepts have equal weight in the subjective evaluation of a visual impact, or whether a concept such as pleasantness is of greater importance.

Finally, the survey results show that every initial landscape requires some degree of protection except landscape D_0, for which the subjects remain indifferent. Furthermore, when the solar farms are incorporated, for no landscape except for landscape D_0 can significant differences in protection values be appreciated. In other words, according to the subjects, it is not important to protect the new landscape D. In other words, according to the subjects, incorporating a solar plant into a rural landscape does not change the degree of protection that this landscape requires.

6. Discussion

6.1. On the results

This work presents a continuation to the methodology introduced by Torres-Sibille et al. [3] who apply the expert approach to develop an indicator of objective aesthetic impact of wind farms. In this investigation, the same methodology is implemented successfully to develop a reliable, and user-friendly indicator of objective aesthetic impact of solar power plants. For this, measures of visibility, colour, fractality and concurrence are combined in a weighting function. These components are inherent in the solar plant itself and can be calculated from photographs.

Similarly to solar energy, wind energy is a type of renewable which requires large expansions of land, and which is often exploited in rural areas. Differences lie in the spatial disposition of the two types of installations. Whereas the elevation of the wind turbines and the large areas necessary for the farm impact along vertical and horizontal dimensions, the impact of solar power plants is limited to large areas of low elevation. Given the different characteristics of the two types of construction, the variables of the indicator have to be adjusted accordingly. For example, the variable continuity is descriptive of the distribution of tall, wind turbines but not of low solar panels, which given their geographical location and differences in panel typologies, are better described by concurrence. Differences in impact values of the remaining variables can also be observed. Generally, because wind turbines occupy a much larger area than do solar panels, the impact due to visibility of the former is much larger; colour and fractality on the other hand are more dependent on background conditions. Nevertheless, the methodology remains the same and gives successful results for both types of construction projects.

The objective study gives a measure of the magnitude of the impact and indicates how each individual component of the plant affects the impact. The subjective study on the other hand, records emotions generated by the impact, as well as the degree to which these emotions are affected. For example, it conveys whether an impact of magnitude X (from the objective study) is perceived as pleasant or not, and gives an indication of just how pleasant (from the subjective study).

Thorough objective and subjective studies can help minimise aesthetic impact in the construction and maintenance phases of the solar power project. Particularly, important is the stimulation of appropriate emotions, which has been found help mitigate the visual impact generated by the plant. Plant components can be adjusted to generate positive reactions in the viewers, in addition to a reduction of impact magnitude. For example, panels without followers as opposed to panels with followers can be used in planar landscapes to reduce fractal contrasts and therefore prevent changes in perceived naturalness. In addition, incorporating this visual impact analysis in the plant's location study will help predict whether the panels will enclose the initial landscape or not.

An interesting result is that generally, a solar plant will not change the degree of protection a viewer attributes the landscape. However, it does reduce its naturalness and affect pleasantness negatively. It will also increase complexity and reduce perceived affection.

Further research is recommended to establish relationships between physical and psychological attributes of aesthetic impact of solar power plants, in order to determine which components and how much of these components generate which reactions. For example, determining which components of plants A, D and E are responsible for the loss in landscape pleasantness, or which attributes of plant D make this landscape differ from the rest, to the point that this is the only plant which generates changes in "protection" values, and what is more, in a negative direction.

6.2. On the methodology

Aesthetic impact consists of objective and subjective components which can be analysed using the expert approach and the public preferences approach, respectively. Initially, the former approach is applied to determine the magnitude of the physical aesthetic quality of a solar plant, and subsequently, the value of the psychological aesthetic quality is calculated using the public preference approach.

In an attempt to develop OAI_{SPP} as objectively as possible, the approach taken in this investigation to calculate impact magnitude is analogous to the expert-based approach, widely used in landscape evaluation. Validity of the indicator is subsequently confirmed in a three-way system: 'Sui validatio', 'Scientatis validatio' and 'Societatis validatio'. Positive results of the analysis of visual impact of wind farms [3] and of solar power plants confirm the applicability of the methodology to visual impact assessment of renewable energies, and encourage its application to further construction projects.

The differential semantics technique has also been applied successfully in previous studies to analyse architectural interiors and consumer products [21–23]. This work supports the validity for the evaluation of the subjective aesthetic impact of a solar plant on a given landscape, and its implementation in general landscape analysis is recommended.

Differential semantics offers a highly reliable easily interpretable means of conversion of qualitative arguments into quantitative evaluations which proves especially useful for Visual Impact Assessment as part of EIA, where impacts are evaluated quantitatively wherever possible. Further research should concentrate on how cognition values arising from differential semantics can be combined with objective magnitudes to produce one final value of aesthetic impact. The authors are researching on these issues and hope to arrive at results very soon.

Both objective and subjective studies are complementary of each other and the authors favour their combined use for the analysis of aesthetic impact. The advantages of carrying out both studies becomes clear if combinations A and B and A–E are compared. For combination A and B, the semantic results show no significant differences between the farms even though the subjects fully agree that A is more impacting than B. For combination A–E on the other hand, although there is no consensus, semantic differences can be appreciated. Even though both combinations present different situations, the conclusion that can be derived from both scenarios is the same. The analysis in Section 5.1 showed that when judging visual impact, the public take into account so much subjective as objective variables. Hence, optimally, any study on aesthetic impact should combine both analyses.

Another example is given by combination A–D. The indicator initially determined that farms A and D were equally impacting. The subjective analysis however, conveyed differences in the emotions; whereas plant A's impact was perceived as pleasant and natural, landscape D was neither pleasant nor natural. Similarly, a subjective study may record no differences in reactions, whereas an objective study could determine that objectively, two farms generate different impacts.

A combination of objective and subjective studies is also encouraged for product design issues. If the purpose is to mitigate or control the aesthetic impact of a new solar power plant (or an

existing plant), a combination of objective and subjective studies is especially useful, as it can integrate consumer perceptions of aesthetic impact in the design phase of the plant. In this work, the magnitude of the impact is calculated from the combination of the impacts generated by five different components. Subsequently, 10 different subjective reactions towards the impact are evaluated using differential semantics. Design changes can vary the objective variables and hence impact magnitude, and it will also generate fluctuations in the axes. The optimal design of a solar plant can be developed accordingly to reach not only appropriate levels of impact magnitude, but also desired reactions from the viewers.

7. Conclusion

In this work, we have developed a composite indicator to determine the objective aesthetic impact of a solar plant located in a defined landscape. For this, the authors have applied the methodology developed by Torres-Sibille et al. [3] who analyse objective aesthetic impact of wind farms. The methodology has proved successful for the analyses of both types of renewable energies and its use for the evaluation of other construction projects is encouraged.

Comparison of the indicator results with a population survey shows that the indicator correctly represents the order of preference resulting from perception of impact. The population survey also proved that aesthetic impact concerns so much objective issues as subjective preferences. A semantic analysis was thus carried out to evaluate the cognitive aspects of aesthetic impact.

The results show that a combination of thorough objective and subjective studies can help control aesthetic impact in the design phase of product development.

Further research is recommended to establish relationships between physical and psychological attributes of aesthetic impact in a holistic approach.

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